Solar Neutrinos: Where We Are, What We Need

John Bahcall

Institute for Advanced Study, Princeton, NJ 08540

This talk compares standard model predictions for solar neutrino experiments with the results of actual observations. Here 'standard model' means the combined standard model of minimal electroweak theory plus a standard solar model. I emphasize the importance of recent analyses in which the neutrino fluxes are treated as free parameters, independent of any constraints from solar models, and the stunning agreement between the predictions of standard solar models and helioseismological measurements. In order to interpret solar neutrino experiments more accurately in terms of fundamental physics and astronomy, we need improved improved nuclear physics data. I describe the five most important nuclear physics problems whose solution is required for understanding the precise implications of solar neutrino experiments.

I. INTRODUCTION

A. Glad to be here

I am very grateful to the organizers for providing me with the opportunity to talk about nuclear physics to nuclear physicists.

Solar neutrino research originated in the attempt to verify experimentally that the sun shines by nuclear fusion reactions among light elements in its interior. During the first few years I worked on the subject, in 1961–1968, almost everyone that had a real interest in solar neutrino research was a nuclear physicist and the things that we most needed to determine for interpreting the proposed experiments were nuclear reaction rates and neutrino absorption cross sections. So, almost everyone I talked to about solar neutrinos in those days was a

nuclear physicist and I enjoyed the experience very much. I am delighted to be back among the physicists of my youth.

Looking around the room, I see many people who have made important contributions to the nuclear physics of solar fusion, the reactions which ultimately determine solar neutrino production. Everyone is grateful for what you have done, but—as you will in the last section of my talk—I still have more requests.

B. Workshop on solar fusion reactions

I want to begin by saying something about a workshop on Solar Fusion Reactions that took place at the Institute for Nuclear Theory of the University of Washington, Seattle, in February 1997.

The goal of the workshop was to determine the best estimates and uncertainties for all of the significant nuclear reactions that determine solar energy generation and solar neutrino production. The organizers of this workshop (J. Bahcall, W. Haxton, P. Parker, and H. Robertson) invited experts to participate representing all specialities and points of view related to nuclear reactions among light elements at low energies. We were astonished that nearly everyone we invited either attended or sent a representative. There were about 40 active participants.

We have only recently submitted to Reviews of Modern Physics [1] a collective report summarizing the state of knowledge for each of the important solar fusion reactions and recommending further work necessary to refine the low energy cross section determinations. I served as the principal editor of this manuscript and accumulated more than 600 substantive emails in the collective process of improving and revising the initial draft conclusions that were reached in Seattle. Essentially everyone who participated in the workshop took an active role in refining our understanding of the experimental and the theoretical situation with respect to all the important solar fusion reactions.

In the last part of this talk, I will make use of this understanding developed by our

joint effort to describe some important unsolved nuclear physics questions whose answers are required for precise interpretations of solar neutrino experiments.

C. Where We Are in Solar Neutrino Research

The four pioneering experiments—chlorine [2,3] Kamiokande [4] GALLEX [5] and SAGE [6]—have all observed neutrino fluxes with intensities that are within a factors of a few of those predicted by standard solar models. Three of the experiments (chlorine, GALLEX, and SAGE) are radiochemical and each radiochemical experiment measures one number, the total rate at which neutrinos above a fixed energy threshold (which depends upon the detector) are captured. The sole electronic (non-radiochemical) detector among the initial experiments, Kamiokande, has shown that the neutrinos come from the sun, by measuring the recoil directions of the electrons scattered by solar neutrinos. Kamiokande has also demonstrated that the observed neutrino energies are consistent with the range of energies expected on the basis of the standard solar model.

The original motivation (in 1964) of solar neutrino experiments was to use the neutrinos "..to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars" [7]. This goal has now been achieved. The four pioneering solar neutrino experiments have established empirically that the stars shine and evolve as the result of nuclear fusion reactions among light elements in their interiors.

However, despite continual refinement of solar model calculations of neutrino fluxes over the past 35 years (see, e.g., the collection of articles reprinted in the book edited by Bahcall, Davis, Parker, Smirnov, and Ulrich [8]), the discrepancies between observations and calculations have gotten worse with time. All four of the initial solar neutrino experiments yield event rates that are significantly less than predicted by standard solar models.

The subject of solar neutrinos is entering a new phase in which large electronic detectors will yield vast amounts of diagnostic data. These new experiments [9–11] will test the prediction of the minimal standard electroweak theory [12–14] that essentially nothing

happens to electron type neutrinos after they are created by nuclear fusion reactions in the interior of the sun. GNO, about which we will hear much in this conference, will provide refined measurements of the low energy part of the solar neutrino spectrum and might, if Nature cooperates and if sufficiently small experimental uncertainties are achieved, establish an upper bound for the *pp* flux that is unachievable in any standard model of the sun.

This talk is organized as follows. I first discuss in section II the three solar neutrino problems. Then I review in section III the recent work by Heeger and Robinson [15] and Hata and Langacker [16] which treats the neutrino fluxes as free parameters and shows that the solar neutrino problems cannot be resolved within the context of minimal standard electroweak theory unless solar neutrino experiments are incorrect. Next I discuss in section IV the stunning agreement between the values of the sound velocity calculated from standard solar models and the values obtained from helioseismological measurements. Finally, in section V I describe some of the most important unsolved problems in nuclear physics the answers to which are required for understanding the implications of solar neutrino experiments.

II. THREE SOLAR NEUTRINO PROBLEMS

I will first compare the predictions of the combined standard model with the results of the operating solar neutrino experiments. By 'combined' standard model, I mean the predictions of the standard solar model and the predictions of the minimal electroweak theory. We need a solar model to tell us how many neutrinos of what energy are produced in the sun and we need electroweak theory to tell us how the number and flavor content of the neutrinos are changed as they make their way from the center of the sun to detectors on earth.

We will see that this comparison leads to three different discrepancies between the calculations and the observations, which I will refer to as the three solar neutrino problems.

Figure 1 shows the measured and the calculated event rates in the four ongoing solar neutrino experiments. This figure reveals three discrepancies between the experimental results and the expectations based upon the combined standard model. As we shall see,

only the first of these discrepancies depends sensitively upon predictions of the standard solar model.

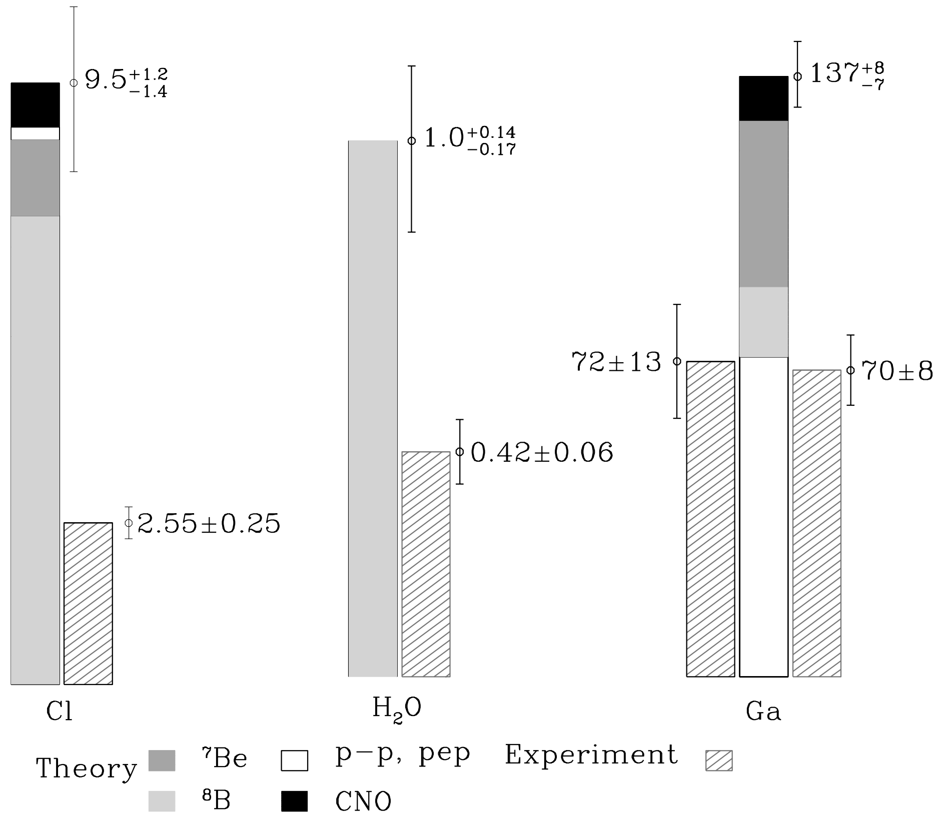

FIG. 1. Comparison of measured rates and standard-model predictions for four solar neutrino experiments.

A. Calculated versus Observed Absolute Rate

The first solar neutrino experiment to be performed was the chlorine radiochemical experiment, which detects electron-type neutrinos that are more energetic than 0.81 MeV. After more than 25 years of the operation of this experiment, the measured event rate is 2.55 ± 0.25 SNU, which is a factor ~ 3.6 less than is predicted by the most detailed theoretical calculations, $9.5^{+1.2}_{-1.4}$ SNU [17,18]. A SNU is a convenient unit to describe the measured rates of solar neutrino experiments: 10^{-36} interactions per target atom per second. Most of the predicted rate in the chlorine experiment is from the rare, high-energy ^{8}B neutrinos, although the ^{7}Be neutrinos are also expected to contribute significantly. According to standard model calculations, the *pep* neutrinos and the CNO neutrinos (for simplicity not

discussed here) are expected to contribute less than 1 SNU to the total event rate.

This discrepancy between the calculations and the observations for the chlorine experiment was, for more than two decades, the only solar neutrino problem. I shall refer to the chlorine disagreement as the "first" solar neutrino problem.

B. Incompatibility of Chlorine and Water (Kamiokande) Experiments

The second solar neutrino problem results from a comparison of the measured event rates in the chlorine experiment and in the Japanese pure-water experiment, Kamiokande. The water experiment detects higher-energy neutrinos, those with energies above 7 MeV, by neutrino-electron scattering: $\nu \ + \ e \ \longrightarrow \nu' \ + \ e'$. According to the standard solar model, ^{8}B beta decay is the only important source of these higher-energy neutrinos.

The Kamiokande experiment shows that the observed neutrinos come from the sun. The electrons that are scattered by the incoming neutrinos recoil predominantly in the direction of the sun-earth vector; the relativistic electrons are observed by the Cherenkov radiation they produce in the water detector.

In addition, the Kamiokande experiment measures the energies of individual scattered electrons and therefore provides information about the energy spectrum of the incident solar neutrinos. The observed spectrum of electron recoil energies is consistent with that expected from ^{8}B neutrinos. However, small angle scattering of the recoil electrons in the water prevents the angular distribution from being determined well on an event-by-event basis, which limits the constraints the experiment places on the incoming neutrino energy spectrum.

The event rate in the Kamiokande experiment is determined by the same high-energy ^{8}B neutrinos that are expected, on the basis of the combined standard model, to dominate the event rate in the chlorine experiment. I have shown [19] that solar physics changes the shape of the ^{8}B neutrino spectrum by less than 1 part in 10^5 . Therefore, we can calculate the rate in the chlorine experiment that is produced by the ^{8}B neutrinos observed in the

Kamiokande experiment (above 7 MeV). This partial (^{8}B) rate in the chlorine experiment is 3.2 ± 0.45 SNU, which exceeds the total observed chlorine rate of 2.55 ± 0.25 SNU.

Comparing the rates of the Kamiokande and the chlorine experiments, one finds that the net contribution to the chlorine experiment from the *pep*, ^{7}Be, and CNO neutrino sources is negative: -0.66 ± 0.52 SNU. The standard model calculated rate from *pep*, ^{7}Be, and CNO neutrinos is 1.9 SNU. The apparent incompatibility of the chlorine and the Kamiokande experiments is the “second” solar neutrino problem. The inference that is often made from this comparison is that the energy spectrum of ^{8}B neutrinos is changed from the standard shape by physics not included in the simplest version of the standard electroweak model.

C. Gallium Experiments: No Room for ^{7}Be Neutrinos

The results of the gallium experiments, GALLEX and SAGE, constitute the third solar neutrino problem. The average observed rate in these two experiments is 70.5 ± 7 SNU, which is fully accounted for in the standard model by the theoretical rate of 73 SNU that is calculated to come from the basic *p-p* and *pep* neutrinos (with only a 1% uncertainty in the standard solar model *p-p* flux). The ^{8}B neutrinos, which are observed above 7.5 MeV in the Kamiokande experiment, must also contribute to the gallium event rate. Using the standard shape for the spectrum of ^{8}B neutrinos and normalizing to the rate observed in Kamiokande, ^{8}B contributes another 7 SNU, unless something happens to the lower-energy neutrinos after they are created in the sun. (The predicted contribution is 16 SNU on the basis of the standard model.) Given the measured rates in the gallium experiments, there is no room for the additional 34 ± 4 SNU that is expected from ^{7}Be neutrinos on the basis of standard solar models.

The seeming exclusion of everything but *p-p* neutrinos in the gallium experiments is the “third” solar neutrino problem. This problem is essentially independent of the previously-discussed solar neutrino problems, since it depends strongly upon the *p-p* neutrinos that are not observed in the other experiments and whose calculated flux is approximately model-

independent.

The missing ^{7}Be neutrinos cannot be explained away by any change in solar physics. The ^{8}B neutrinos that are observed in the Kamiokande experiment are produced in competition with the missing ^{7}Be neutrinos; the competition is between electron capture on ^{7}Be versus proton capture on ^{7}Be. Solar model explanations that reduce the predicted ^{7}Be flux generically reduce much more (too much) the predictions for the observed ^{8}B flux.

The flux of ^{7}Be neutrinos, $\phi(^7\mathrm{Be})$, is independent of measurement uncertainties in the cross section for the nuclear reaction $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$; the cross section for this proton-capture reaction is the most uncertain quantity that enters in an important way in the solar model calculations. The flux of ^{7}Be neutrinos depends upon the proton-capture reaction only through the ratio

$$\phi(^7\mathrm{Be}) \ \propto \ \frac{R(e)}{R(e)+R(p)}, \qquad (1)$$

where $R(e)$ is the rate of electron capture by ^{7}Be nuclei and $R(p)$ is the rate of proton capture by ^{7}Be. With standard parameters, solar models yield $R(p) \approx 10^{-3}R(e)$. Therefore, one would have to increase the value of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section by more than 2 orders of magnitude over the current best-estimate (which has an estimated uncertainty of $\sim 10\%$) in order to affect significantly the calculated ^{7}Be solar neutrino flux. The required change in the nuclear physics cross section would also increase the predicted neutrino event rate by more than 100 in the Kamiokande experiment, making that prediction completely inconsistent with what is observed. (From time to time, papers have been published claiming to solve the solar neutrino problem by artificially changing the rate of the ^{7}Be electron capture reaction. Equation (1) shows that the flux of ^{7}Be neutrinos is actually independent of the rate of the electron capture reaction to an accuracy of better than 1%.)

I conclude that either: 1) at least three of the four operating solar neutrino experiments (the two gallium experiments plus either chlorine or Kamiokande) have yielded misleading results, or 2) physics beyond the standard electroweak model is required to change the neutrino energy spectrum (or flavor content) after the neutrinos are produced in the center

of the sun.

III. "THE LAST HOPE": NO SOLAR MODEL

The clearest way to see that the results of the four solar neutrino experiments are inconsistent with the predictions of the minimal electroweak model is not to use standard solar models at all in the comparison with observations. This is what Berezinsky, Fiorentini, and Lissia [20] have termed "The Last Hope" for a solution of the solar neutrino problems without introducing new physics.

Let me now explain how model independent tests are made.

Let $\phi_i(E)$ be the normalized shape of the neutrino energy spectrum from one of the i neutrino sources in the sun (e.g., ^{8}B or $p-p$ neutrinos). I have shown [19] that the shape of the neutrino energy spectra that result from radioactive decays, ^{8}B, ^{13}N, ^{15}O, and ^{17}F, are the same to 1 part in 10^5 as the laboratory shapes. The $p-p$ neutrino energy spectrum, which is produced by fusion has a slight dependence on the solar temperature, which affects the shape by about 1%. The energies of the neutrino lines from ^{7}Be and *pep* electron capture reactions are also only slightly shifted, by about 1% or less, because of the thermal energies of particles in the solar core.

Thus one can test the hypothesis that an arbitrary linear combination of the normalized neutrino spectra,

$$\Phi(E) \ = \ \sum_i \alpha_i \phi_i(E), \tag{2}$$

can fit the results of the neutrino experiments. One can add a constraint to Eq. (2) that embodies the fact that the sun shines by nuclear fusion reactions that also produce the neutrinos. The explicit form of this luminosity constraint is

$$\frac{L_\odot}{4\pi r^2} = \sum_j \beta_j \phi_j \ , \tag{3}$$

where the eight coefficients, β_j, are given in Table VI of the paper by Bahcall and Krastev [21].

The first demonstration that the four pioneering experiments are by themselves inconsistent with the assumption that nothing happens to solar neutrinos after they are created in the core of the sun was by Hata, Bludman, and Langacker [22]. They showed that the solar neutrino data available by late 1993 were incompatible with any solution of equations (2) and (3) at the 97% C.L.

The most recent and complete published analysis in which the neutrino fluxes are treated as free parameters is by Heeger and Robertson [15] who showed that the data presented at the Neutrino '96 Conference in Helsinki are inconsistent with equations (2) and (3) at the 99.5% C.L. Even if they omitted the luminosity constraint, equation (3), they found inconsistency at the 94% C.L. Similar results have been presented by Hata and Langacker [16].

IV. COMPARISON WITH HELIOSEISMOLOGICAL MEASUREMENTS

Helioseismology has recently sharpened the disagreement between observations and the predictions of solar models with standard (non-oscillating) neutrinos. This development has occurred in two ways.

Helioseismology has confirmed the correctness of including diffusion in the solar models and the effect of diffusion leads to somewhat higher predicted events in the chlorine and Kamiokande solar neutrino experiments [17]. Even more importantly, helioseismology has demonstrated that the sound velocities predicted by standard solar models agree with extraordinary precision with the sound velocities of the sun inferred from helioseismological measurements [18]. Because of the precision of this agreement, I am convinced that standard solar models cannot be in error by enough to make a major difference in the solar neutrino problems.

I will report here on some comparisons that Marc Pinsonneault, Sarbani Basu, Jøergen, and I have done recently which demonstrate the precise agreement between the sound velocities in standard solar models and the sound velocities inferred from helioseismological measurements [18].

Since the deep solar interior behaves essentially as a fully ionized perfect gas, $c^2 \propto T/\mu$ where T is temperature and μ is mean molecular weight. The sound velocities in the sun are determined from helioseismology to a very high accuracy, better than 0.2% rms throughout nearly all the sun. Thus even tiny fractional errors in the model values of T or μ would produce measurable discrepancies in the precisely determined helioseismological sound speed

$$\frac{\delta c}{c} \simeq \frac{1}{2}\left(\frac{\delta T}{T} - \frac{\delta \mu}{\mu}\right) . \tag{4}$$

The remarkable numerical agreement between standard predictions and helioseismological observations, which I will discuss in the following remarks, rules out solar models with temperature or mean molecular weight profiles that differ significantly from standard profiles. The helioseismological data essentially rule out solar models in which deep mixing has occurred (cf. [18,23]) and argue against unmixed models in which the subtle effect of particle diffusion–selective sinking of heavier species in the sun's gravitational field–is not included.

Figure 2 compares the sound speeds computed from two different solar models with the values inferred [24,25] from the helioseismological measurements. The best standard model of Bahcall and Pinsonneault (BP) [17], which includes helium and heavy element diffusion and recent improvements [26,27] in the OPAL equation of state and opacities is represented by the dark line; the corresponding BP model without diffusion is represented by the dashed line. For the standard model, the rms discrepancy between predicted and measured sound speeds is 0.1% (which may be due partly to systematic uncertainties in the data analysis).

In the outer parts of the sun, in the convective region between $0.7R_\odot$ to $0.95R_\odot$ (where the measurements end), the No Diffusion model disagrees with the observations by as much as 0.5% (see Figure 2).

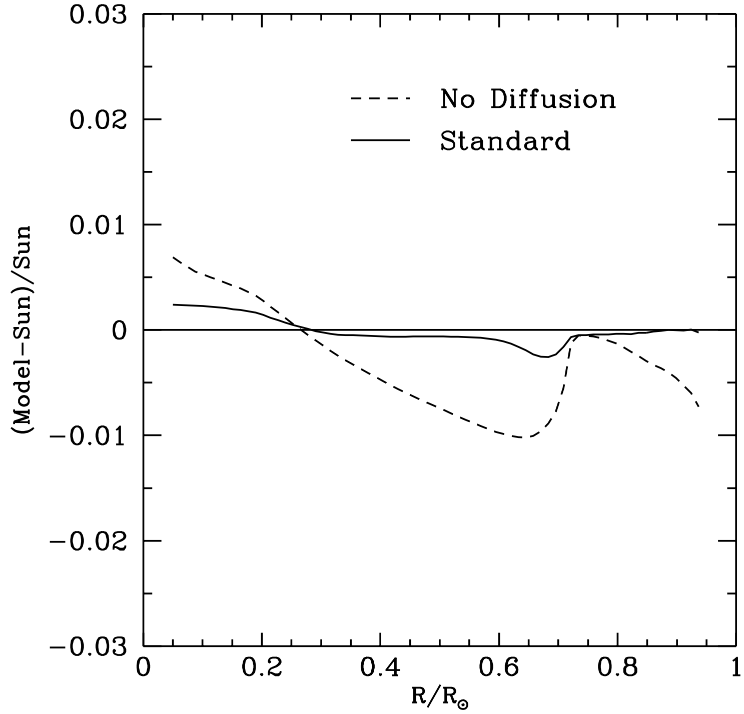

FIG. 2. Comparison of sound speeds predicted by different standard solar models with the sound speeds measured by helioseismology. There are no free parameters in the models. The figure shows the fractional difference, $\delta c/c$, between the predicted model sound speed and the measured [24,25] solar values as a function of radial position in the sun ($R_\odot$ is the solar radius). The dashed line refers to a model [17] in which diffusion is neglected and the dark line represents a model [17] which includes diffusion and recent improvements in the OPAL equation of state and opacities [26,27]. This figure is adapted from [18].

The agreement between standard models and solar observations is independent of the finer details of the solar model. The standard model of Christensen-Dalsgaard *et al.* [28], which is derived from an independent computer code with different descriptions of the microphysics, predicts solar sound speeds that agree everywhere with the measured speeds to better than 0.2%.

Equation 4 and Figure 2 imply that any changes $\delta T/T$ from the standard model values of temperature must be almost exactly canceled by changes $\delta\mu/\mu$ in mean molecular weight. In the standard model, T and μ vary, respectively, by a factor of 53 and 43% over the entire range for which c has been measured and by 1.9 and 39% over the energy producing region. It would be a remarkable coincidence if nature chose T and μ profiles that individually differ markedly from the standard model but have the same ratio T/μ. Thus we expect

that the fractional differences between the solar and the model temperature, $\delta T/T$, or mean molecular weights, $\delta\mu/\mu$, are of similar magnitude to $\delta c^2/c^2$, i.e. (using the larger rms error, 0.002, for the solar interior),

$$|\delta T/T|,\ |\delta\mu/\mu| \ \lesssim\ 0.004. \tag{5}$$

How significant for solar neutrino studies is the agreement between observation and prediction that is shown in Figure 2? The calculated neutrino fluxes depend upon the central temperature of the solar model approximately as a power of the temperature, Flux $\propto T^n$, where for standard models the exponent n varies from $n \sim -1.1$ for the $p-p$ neutrinos to $n \sim +24$ for the ^{8}B neutrinos [29]. Similar temperature scalings are found for non-standard solar models [30]. Thus, maximum temperature differences of $\sim 0.2\%$ would produce changes in the different neutrino fluxes of several percent or less, much less than required [31] to ameliorate the solar neutrino problems.

Helioseismology rules out all solar models with large amounts of interior mixing, unless finely-tuned compensating changes in the temperature are made. The mean molecular weight in the standard solar model with diffusion varies monotonically from 0.86 in the deep interior to 0.62 at the outer region of nuclear fusion ($R = 0.25R\odot$) to 0.60 near the solar surface. Any mixing model will cause μ to be constant and equal to the average value in the mixed region. At the very least, the region in which nuclear fusion occurs must be mixed in order to affect significantly the calculated neutrino fluxes [32–36]. Unless almost precisely canceling temperature changes are assumed, solar models in which the nuclear burning region is mixed ($R \lesssim 0.25R_\odot$) will give maximum differences, δc, between the mixed and the standard model predictions, and hence between the mixed model predictions and the observations, of order

$$\frac{\delta c}{c} \ =\ \frac{1}{2}\left(\frac{\mu - <\mu>}{\mu}\right)\ \sim\ 7\% \text{ to } 10\%, \tag{6}$$

which is inconsistent with Figure 2.

To me, these results suggest that the assumption on which they are based—nothing happens to the neutrinos after they are created in the interior of the sun—is incorrect.

V. WHAT DO WE NEED TO KNOW FROM NUCLEAR PHYSICISTS?

Here are the most important things that we need to know from nuclear physicists.

- **The rate of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction**

The rate at low energies ($\sim$ 20 keV) of this reaction has been for 30 years both the most uncertain and the most important nuclear parameter for interpreting solar neutrino experiments. The ^{8}B reaction is so rare that it does not affect solar structure; therefore, the rate observed in present and future solar neutrino experiments like Kamiokande, Super-Kamiokande, ICARUS, and SNO (as well as most of the rate in the chlorine solar neutrino experiment) is directly proportional to the uncertain laboratory cross section. Unfortunately, there is only one well documented experiment at the required low energies (below 300 keV) and this experiment was published in 1983 by Filippone and his collaborators. [37]

Solar neutrino experiments will soon determine the observed flux of ^{8}B neutrinos to an accuracy of better than 1% (typical rates in Super-Kamiokande and SNO will be about 5000 events per year). Therefore, the limiting factor for interpreting the ^{8}B neutrino flux for fundamental physics and fundamental astronomy will be the knowledge of the low energy cross section factor, which is at present determined experimentally to only about 4 parts in 19 (1σ).

I am most concerned about systematic errors in the experiments. Fortunately, we have several international experiments that will measure the ^{8}B solar neutrino flux, but we do not have that felicitous situation for the low energy $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ laboratory measurement. The most critical measurement would be with a radioactive beam of ^{7}Be since that would have different systematic uncertainties from the more conventional experiments, performed or planned, with a proton beam on a ^{7}Be target.

It is also extremely important to perform measurements at very low energies, even below 100 keV, with an implanted ^{7}Be target. Measurements of this kind are essential to obtain a precise extrapolation of the rate of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction to the low energies characteristic of solar fusion.

A measurement of the ^{7}Be quadrupole moment would help distinguish between different nuclear models for the ^{7}Be$(p,\gamma)^8$B reaction (see [38]).

We also need a comprehensive discussion of the uncertainties associated with the theoretical extrapolations. How constrained are the extrapolations obtained using different nuclear physics models? Is it possible to make a model which is consistent with all the experimental data and does not exhibit a slight upturn at very low energies? Can one define limits, established by the existing experiments, to the theoretical uncertainties?

- **The ^{3}He(^{3}He, $2p$)^{4}He reaction.**

The only major solar fusion reaction that has so far been studied in the region of the Gamow energy peak is the ^{3}He(^{3}He, $2p$)^{4}He reaction. A really beautiful experiment has been performed by Arpesella *et al.*. [39] For the first time, these authors have obtained data that determines rather well the cross section in the vicinity of the Gamow Peak at about 20 keV. The results agree well with theoretical extrapolations, providing validation for the general procedure of extrapolating nuclear reaction measurements to low energies in order to predict solar fusion rates. However, because this reaction is so important—it terminates about 85% of the fusions in the $p-p$ chain according to the standard solar model—a more detailed study at low energies is required, with special attention to the region between 15 keV and 60 keV.

- **The ^{3}He(α,γ)^{7}Be reaction**

This reaction leads directly to the ^{8}B and ^{7}Be neutrino production that are the focus of current solar neutrino experiments. Moreover, the ^{3}He(α,γ)^{7}Be reaction occurs in about 85% of the terminations of the $p-p$ chain according to the standard solar model.

The six published measurements of the ^{3}He(α,γ)^{7}Be reaction made by direct capture differ by about 2.5σ from the measurements made using activity measurements (see [1]). Additional precision experiments that could clarify the origin of this apparent difference would be very valuable. It would also be important to make measurements of the cross section for the ^{3}He(α,γ)^{7}Be reaction at energies closer to the Gamow peak.

- **The $^{14}N(p,\gamma)^{15}O$ reaction**

The $^{14}N(p,\gamma)^{15}O$ reaction plays the dominant role in determining the rate of energy generation of the CNO cycle, but the rate of this reaction is not well known. The most important uncertainties concern the size of the contribution to the total rate of a subthreshold state and the absolute normalization of the low-energy cross-section data. New measurements with modern techniques are required.

- **The $p-p$ reaction**

One of the largest uncertainties (2%) in the calculation of the $p-p$ reaction rate is caused by corrections to the nuclear matrix element for the exchange of π and ρ mesons [40,41] which arise from nonconservation of the axial-vector current. Two of the most recent and important calculations of this effect take into account ρ as well as π exchange. [42,43]

There are people in the audience today who could make further improvements on these calculations using the constraints provided by existing data, including the measured ^3H lifetime.

VI. DISCUSSION

The combined predictions of the standard solar model and the standard electroweak theory disagree with the results of the four pioneering solar neutrino experiments. The disagreement persists even if the neutrino fluxes are treated as free parameters, without reference to any solar model.

The solar model calculations are in excellent agreement with helioseismological measurements of the sound velocity, providing further support for the inference that something happens to the solar neutrinos after they are created in the center of the sun.

In order to put the present situation somewhat in perspective, I would like to look backwards for a moment. Considering what was envisioned in 1964 [7], I am astonished with what has been accomplished. In 1964, it was not clear that solar neutrinos could be detected. Now, solar neutrinos have been observed in five different experiments and the

theory of stellar energy generation by nuclear fusion has been directly confirmed. Moreover, particle theorists have shown that solar neutrinos can be used to study neutrino properties, a possibility that we did not even consider in 1964. In fact, much of the interest in the subject stems from the fact that the pioneering experiments suggest that new neutrino physics may be revealed by solar neutrino measurements. Finally, helioseismology has confirmed to high precision predictions of the standard solar model, a possibility that also was not imagined in 1964.

We can look forward with confidence to the revelations of the new series of experiments, Super-Kamiokande, GNO, SNO, BOREXINO, and ICARUS. Whatever Nature has in store for us, the last thirty years suggest that the revelations of the future will be beautiful and fun and, most likely, surprising.

ACKNOWLEDGMENTS

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